Strong Yukawa bound states at LHC

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Phys. Rev. D. 84, (2011), arXiv:1109.3382

Outline

- Introduction
- Strong Yukawa-bound states
  - Relativistic expansion and Bethe-Salpeter
  - Spectrum
- Phenomenology
- Discussion & Conclusion

Introduction

Fourth generation

Baryon Asymmetry of the Universe

W.-S. Hou, Chin. J. Phys. 47, 134 (2009) [arXiv: hep- ph/0803.1234].

Could Strong Yukawa be part of EWSB?

Y. Nambu, EFI preprint 89-08 (1989).
B. Holdom, Phys. Rev. Lett. 57, 2496 (1986).
W.A. Bardeen, C.T. Hill and M. Lindner, Phys. Rev. D 41, 1647 (1990).

Experimental searches of 4G at CMS

at 95% C.L. $m_{t'} > 450\, GeV$

G. Tonelli, EPS Conference on High-Energy Physics, 2011, Grenoble

$m_{b'} > 495\, GeV$

A. De Roeck, Lepton Photon Symposium, 2011, Mumbai

Soon could reach to ~ 550 GeV & 600 GeV respectively

Theoretical constraints

Perturbative Unitarity → $m_{t'}\,,\, m_{b'} \lesssim 550\, GeV$

M.S. Chanowitz, M.A. Furman and I. Hinchliffe,
Phys. Lett. B 78, 285 (1978); Nucl. Phys. B 153, 402 (1979).

Dynamical arguments → $m_Q \lesssim 3\, TeV, \;\; Q = t', b'$

M.B. Einhorn and G.J. Goldberg, Phys. Rev. Lett. 57, 2115 (1986)

EW Precision Constraint → $m_{t'} - m_{b'} \lesssim O(50\, GeV)$

We take $m_Q \equiv m_{t'} = m_{b'}$

New Heavy "*Isospin*" *of 4G!*

We consider 4G quark mass region

$$500\,\mathrm{GeV} \lesssim m_Q \lesssim 700\,\mathrm{GeV}$$

Yukawa-coupling is strong, QCD subdominant

$$0.66 \lesssim \alpha_Y \equiv \frac{m_Q^2}{4\pi v^2} \lesssim 1.3 \;\; vs \;\; \alpha_s = 0.1$$

⬇

New Yukawa-bound states of Heavy 4G at LHC!

Heavy "Isospin" determines the spectrum

isovectors $\pi_{(1,8)}, \rho_{(1,8)} \sim [(\bar{t}'t' - \bar{b}'b')/\sqrt{2},\; \bar{t}'b',\; \bar{b}'t']$

isosinglets $\eta_{(1,8)}, \omega_{(1,8)} \sim (\bar{t}'t' + \bar{b}'b')/\sqrt{2}$

The total potential for Heavy $\bar{Q}Q$ "*Mesons*"

$$V = V_{higgs} + V_{Goldstone} + V_{gluon}$$

- V_{higgs}: $m_h \gtrsim 600\,\mathrm{GeV}$ for SM4
- $V_{Goldstone}$: $m_G \sim M_W$ dominant
- V_{gluon}: Subdominant

States	C, I, S	Higgs	Goldstone	Gluon
(π_1, ω_1)	$\mathbf{1}, (1, 0), (0, 1)$	$-$	$-$	$-$
(π_8, ω_8)	$\mathbf{8}, (1, 0), (0, 1)$	$-$	$-$	$+$
(η_1, ρ_1)	$\mathbf{1}, (0, 1), (0, 1)$	$-$	$+$	$-$
(η_8, ρ_8)	$\mathbf{8}, (0, 1), (0, 1)$	$-$	$+$	$+$

$-$:attractive, $+$:repulsive, C :Color, I :Isospin, S :Spin

Possible spectrum:

$$m_{\pi_1} \lesssim m_{\omega_1} \lesssim m_{\pi_8} \lesssim m_{\omega_8}$$

"eta" and "rho" channels are unbound

No "rho"-like state in clear contrast with Technicolor!

Relativistic Bethe-Salpeter approach

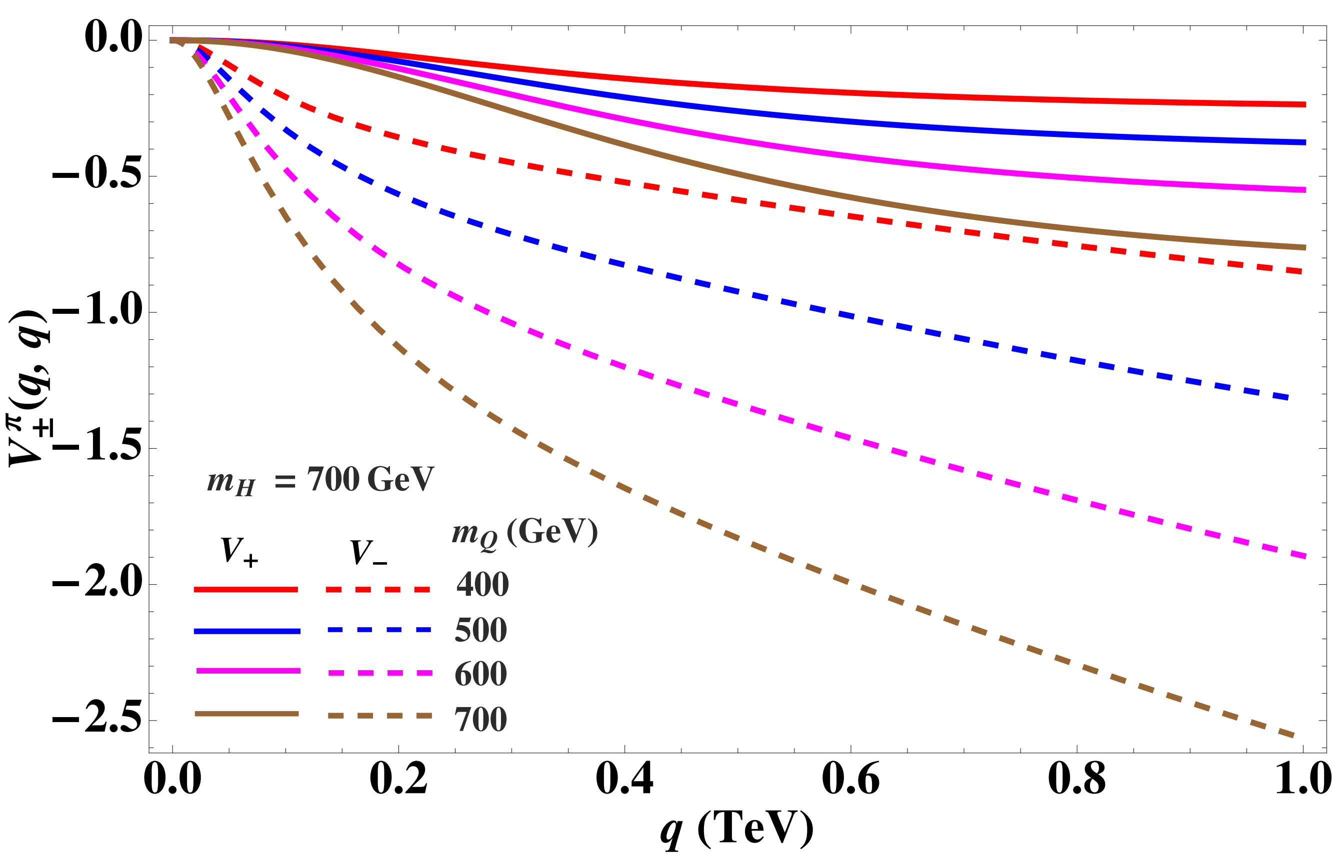
P. Jain et al., Phys. Rev. D 46, 4029 (1992); ibid. D 49, 2514 (1994)

Bethe-Salpeter equation for π_1 state

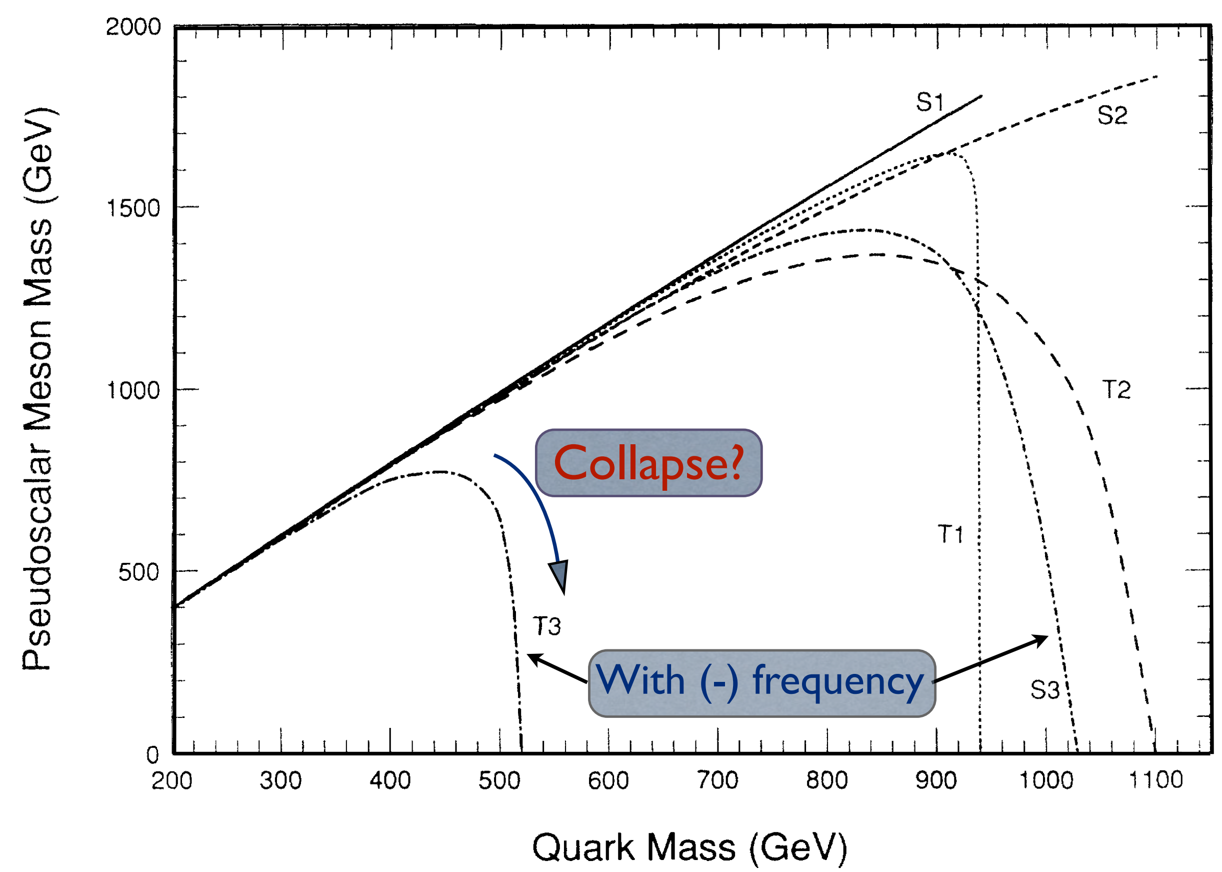
$$(M \mp 2\omega)\chi^{\pi}_{\pm}(q) = \pm \int dq' \frac{q'}{q} \left[V^{\pi}_{\pm}(q, q')\chi^{\pi}_{+}(q') + V^{\pi}_{\mp}(q, q')\chi^{\pi}_{-}(q')\right]$$

$\chi^{\pi}_{\pm}(q)$ -bound state ampl. for $\pm$ freq. at q-momentum exch.

$\pm$ potentials for π_1 state



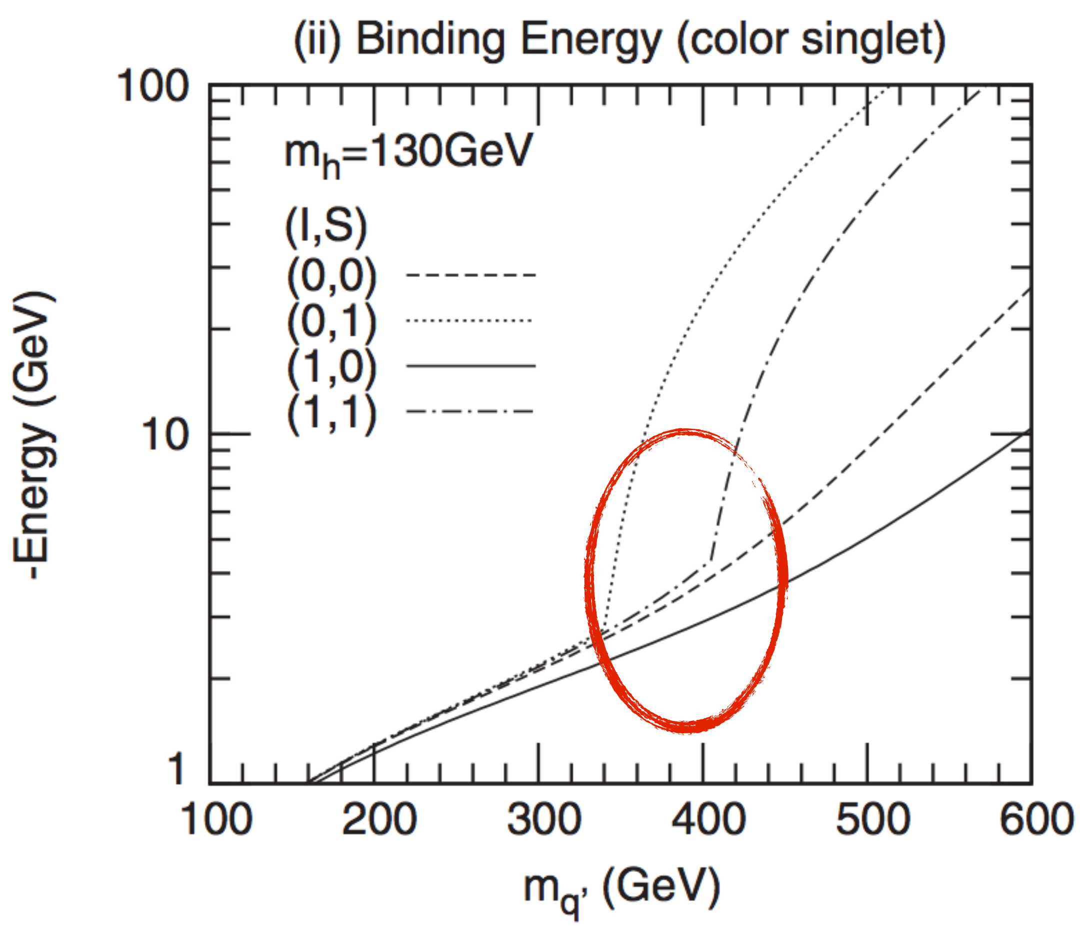
Quark mass vs meson mass

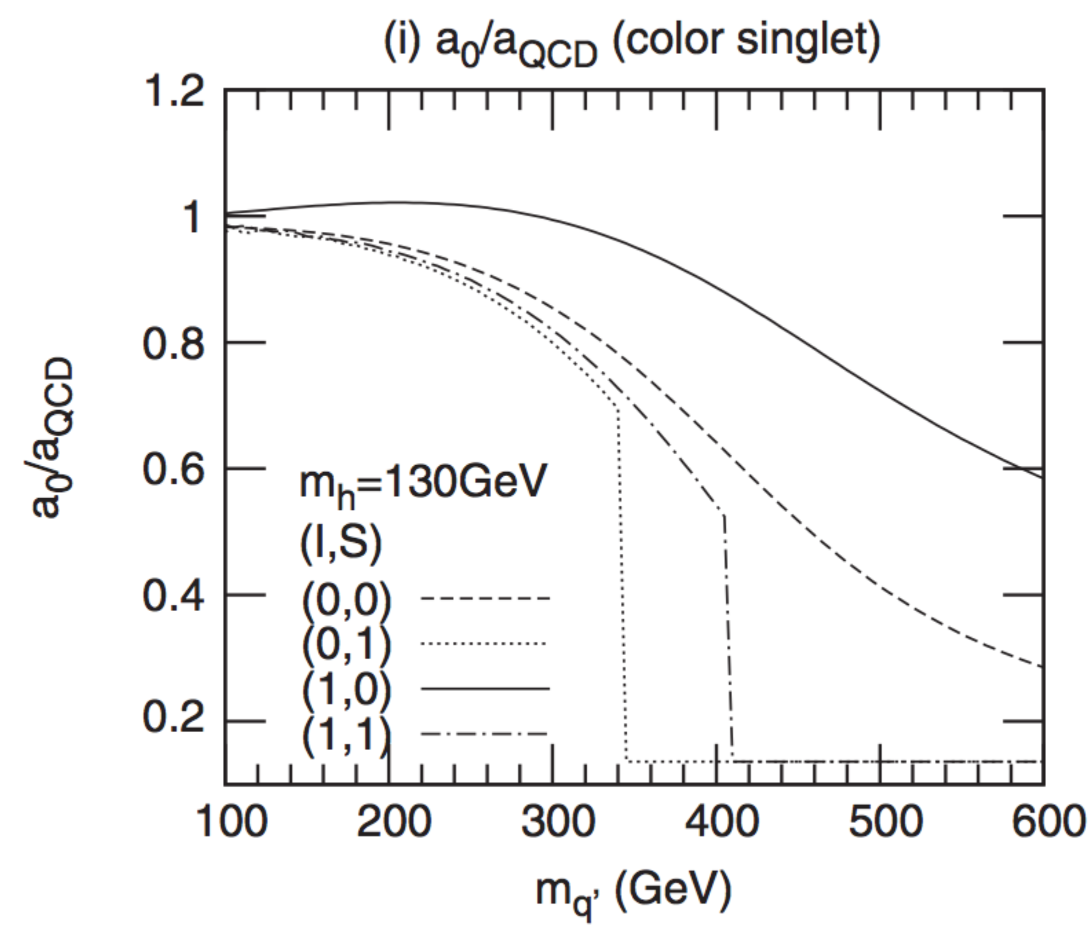


Relativistic expansion for Yukawa-bound system

K. Ishiwata and M.B. Wise, Phys. Rev. D 83, 074015 (2011)

Binding energy and radius a_0 vs m_Q valid for $a_0 > \sqrt{3}/m_Q$





	(C, I, S)	Lower limit of $m_{q'}$
η_8	$(\mathbf{8}, 0, 0)$	No bound state
ω_8	$(\mathbf{8}, 0, 1)$	534 GeV
π_8	$(\mathbf{8}, 1, 0)$	534 GeV
ρ_8	$(\mathbf{8}, 1, 1)$	696 GeV

★ No - freq. contribution
π_8-ω_8 degeneracy
ρ_8 is bound

Which one is interesting for early LHC data?

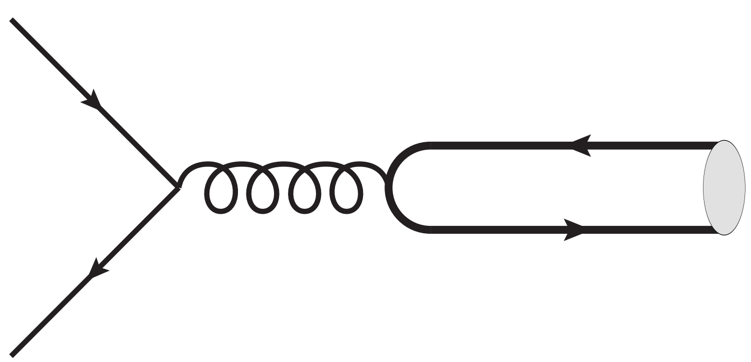
$\pi_1,\ \omega_1$ produced in weak Drell-Yang, no gg-fusion

π_8 *pair* produced in strong, singly produced in weak processes

Not efficiently produced

For early LHC phenomenology color-octet, isosinglet vector meson ω_8 is the most interesting.

ω_8 produced in $q\bar{q}$-fusion, no gg-fusion (Young's theorem)



$$< 0|V^{\mu,a}|\omega_8^b(p) > \equiv \delta^{ab}\frac{1}{\sqrt{2}} f_{\omega_8} m_{\omega_8} \epsilon^\mu(p)$$

Decay constant parameter

$$\xi \equiv \frac{f_{\omega_8}}{m_{\omega_8}}$$

Parton-level cross-section

$$\hat{\sigma}_{q\bar{q}\to\omega_8}(\hat{s}) = \frac{32\pi^3\alpha_s^2}{9m_{\omega_8}^2}\xi^2\delta\left(1 - m_{\omega_8}^2/\hat{s}\right)$$

Hadron-level cross-section

$$\sigma(s) = \int d\hat{\tau}\,\hat{\sigma}(\hat{\tau}s)\,\mathcal{L}(\hat{\tau};\mu_F^2)$$

Parton luminosity

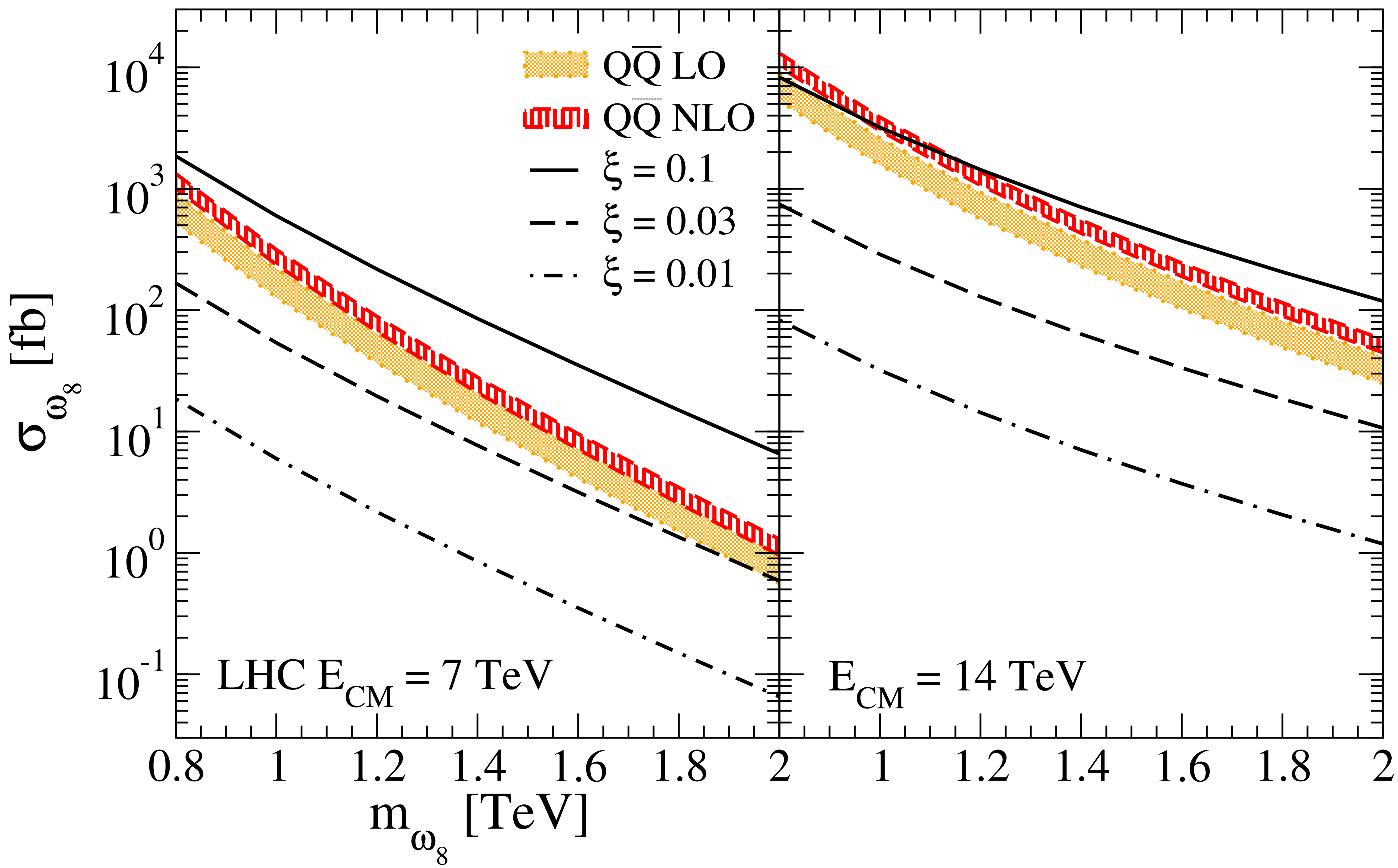
$$\mathcal{L}(\tau;\mu_F^2) = \int\int dx_1 dx_2 f_1(x_1;\mu_F^2) f_2(x_2;\mu_F^2)\delta\left(\tau - x_1x_2\right)$$

PDFs

Scales are varied

$\mu_R = \mu_F = m_Q$ to $4m_Q$ for open production uncertainty (qq-bar pair)

Production of ω_8



Open production of $\bar{Q}Q$ pair is shown in yellow (red) band at LO (NLO)

☆ Heavy "meson" could be dominant for large decay const

Decay channels of ω_8

Three main decay mechanisms

Annihilation decay $\omega_8 \to q\bar{q}, t\bar{t}, t'\bar{t}, b'\bar{b}$

$$\Gamma(\omega_8 \to q\bar{q}) = \xi^2 \frac{\pi\alpha_s^2}{3} m_{\omega_8} n_f$$

$$\Gamma(\omega_8 \to t\bar{t}) = \xi^2 \frac{\pi\alpha_s^2}{3} m_{\omega_8} \beta_t$$

$$\Gamma(\omega_8 \to t\bar{t}') = \xi^2 |V_{tb'}^* V_{t'b'}|^2 \frac{G_F^2 m_{\omega_8}^5}{192\pi}$$

Free quark decay $\omega_8 \to (t'\bar{t}' \to bW\bar{t}'), (b'\bar{b}' \to tW\bar{b}')$

$$\Gamma_{\rm free} \simeq \Gamma_{t'} + \Gamma_{b'}$$

$$\Gamma_{t'} = |V_{t'b}|^2 \frac{G_F m_{t'}^3}{8\sqrt{2}\pi} F(\tilde{m}_W, \tilde{m}_b)$$

$V_{t'b}$ -4th & 3d generation mixing

Meson transition $\omega_8 \to \pi_8 W,\ \omega_1 g$

$$\Gamma(\omega_8 \to \pi_8 W) = \frac{G_F m_{\omega_8}^3}{32\sqrt{2}\pi} \frac{m_{\omega_8}}{m_{\pi_8}} W(\hat{m}_{\pi_8}, \hat{m}_W)$$

$$\Gamma(\omega_8 \to \omega_1 g) = \frac{\alpha_s}{18} \frac{m_{\omega_8}^2}{m_{\omega_1}} G(\hat{m}_{\omega_1})$$

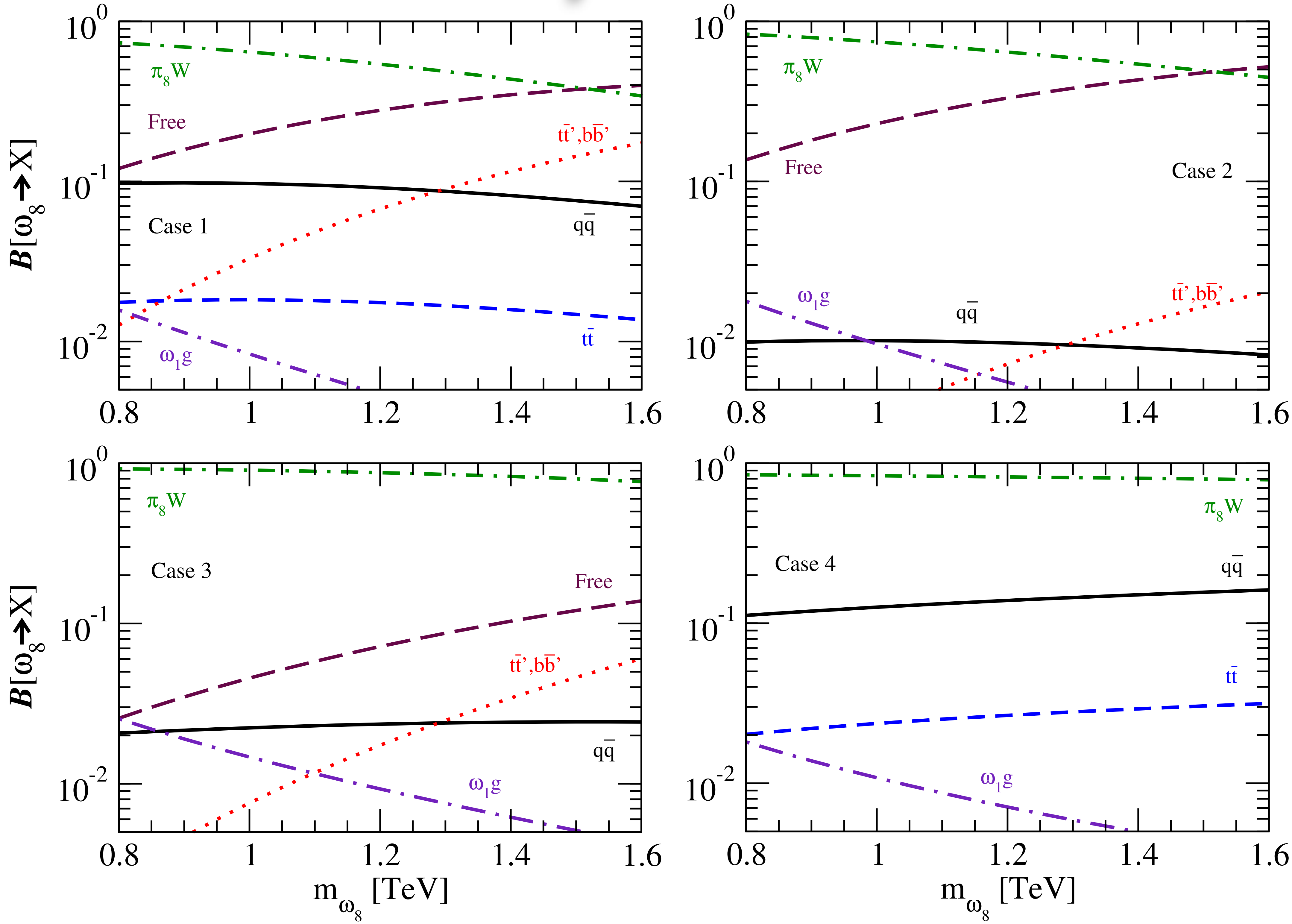
$$\Gamma(\omega_8 \to \pi_8 \gamma) \simeq \frac{\alpha}{3} \frac{(\Delta m)^3}{m_Q^2}$$

Here $\Delta m \equiv m_{\omega_8} - m_{\pi_8}$ due to Strong binding

Four different choices for parameters for decay rate calculation

Case 1	$\xi = 0.1, \Delta m = 100\ GeV, V_{t'b} = 0.1$	"nominal"
Case 2	$\xi = 0.03, \Delta m = 100\ GeV, V_{t'b} = 0.1$	"small f_{ω_8}"
Case 3	$\xi = 0.1, \Delta m = 200\ GeV, V_{t'b} = 0.1$	"strong binding"
Case 4	$\xi = 0.1, \Delta m = 100\ GeV, V_{t'b} = 0.01$	"small mixing"

Decay rates of ω_8

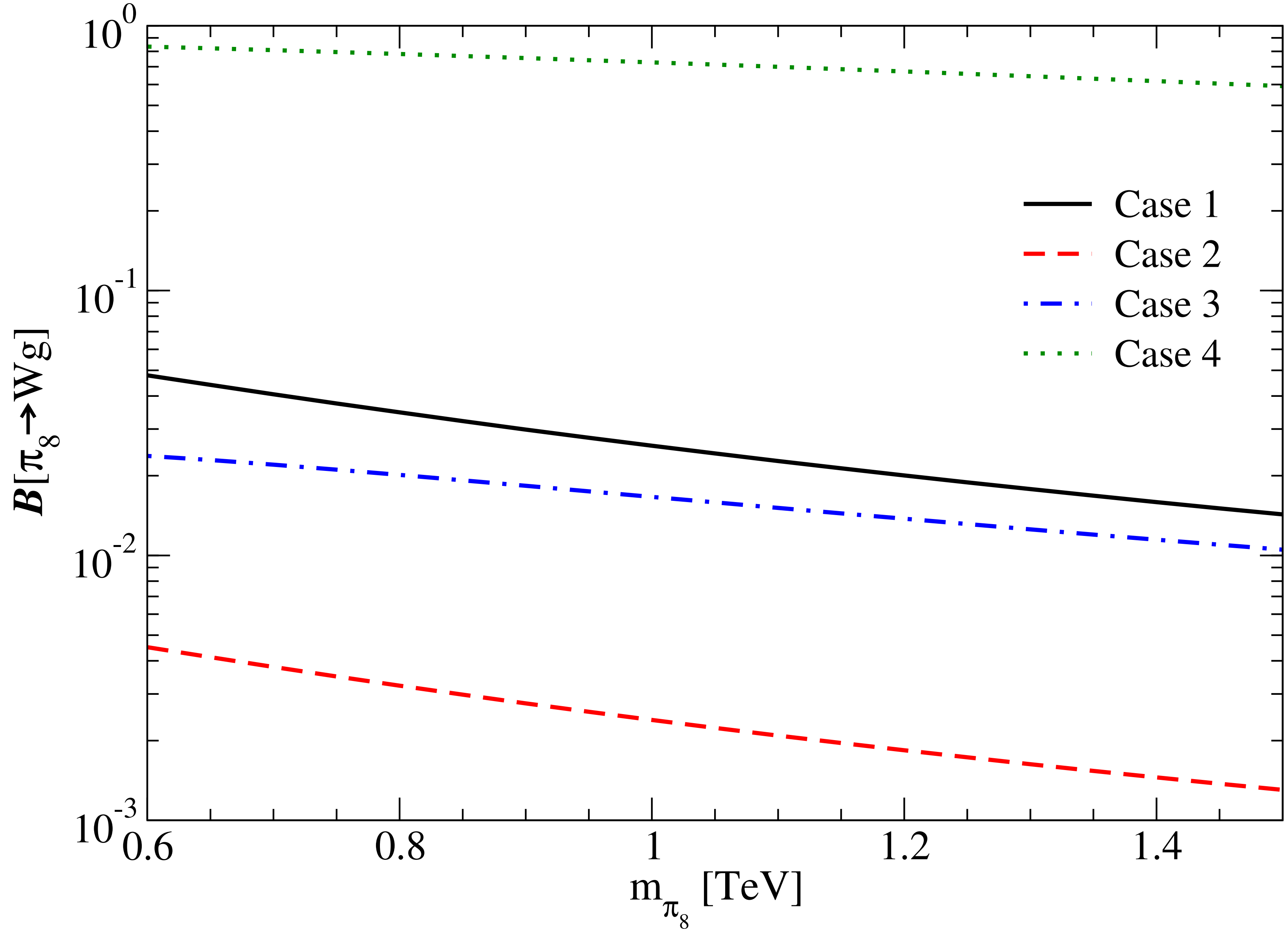


Meson transition $\omega_8 \to \pi_8 W$ dominates
If $\Delta m < M_W$, free or dijet are dominant

Branching ratio for of $\pi_8 \to W g$

Only free quark or $\pi_8 \to W g$ decays channels

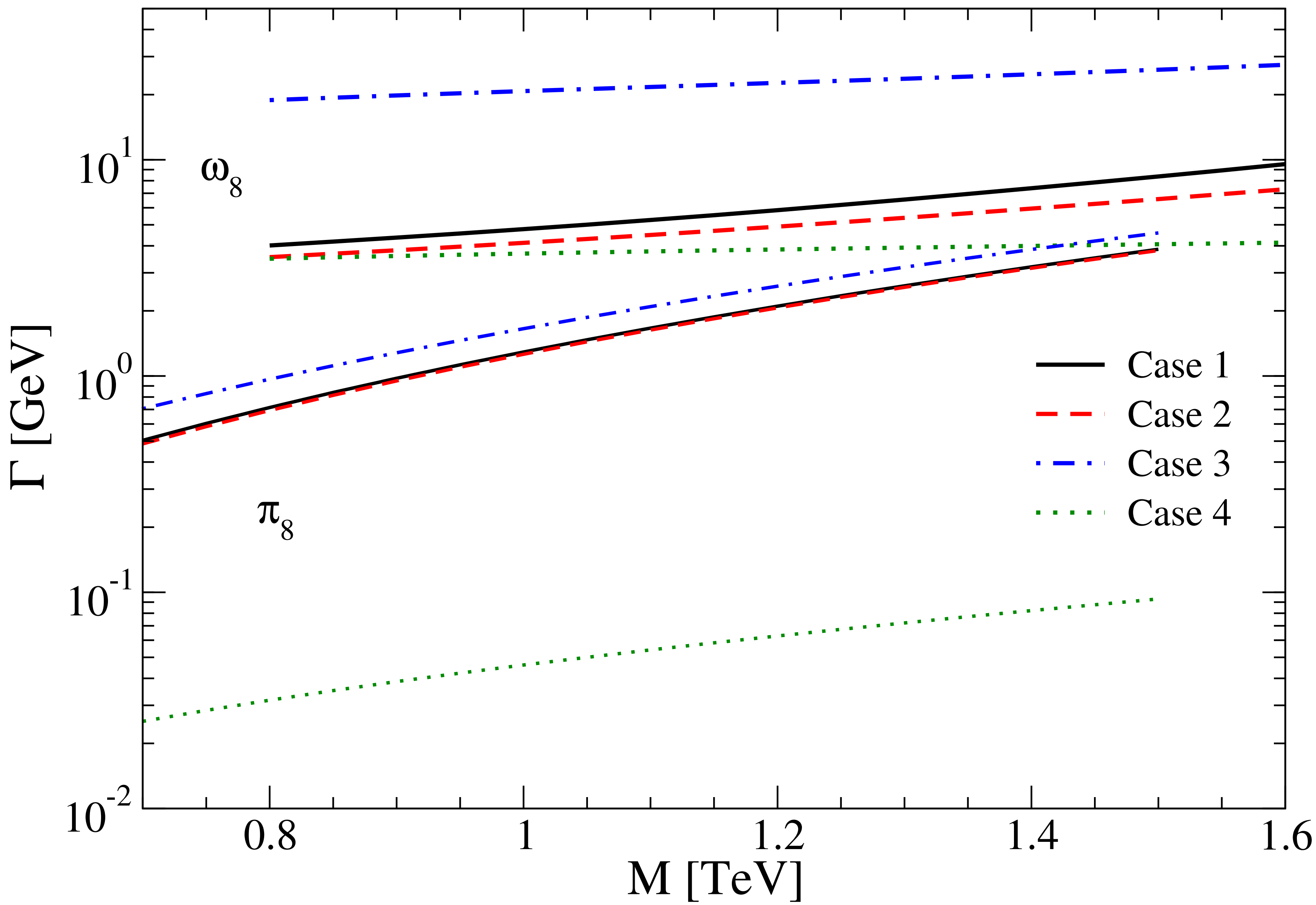
Annihilation s-channel or *W*-exch and $\pi_8 \to \pi_1 g$ are absent.



For cases 1 to 3 the free quark decay dominates

For case 4, $\pi_8 \to W g$ dominates

Total decay width of ω_8 and π_8

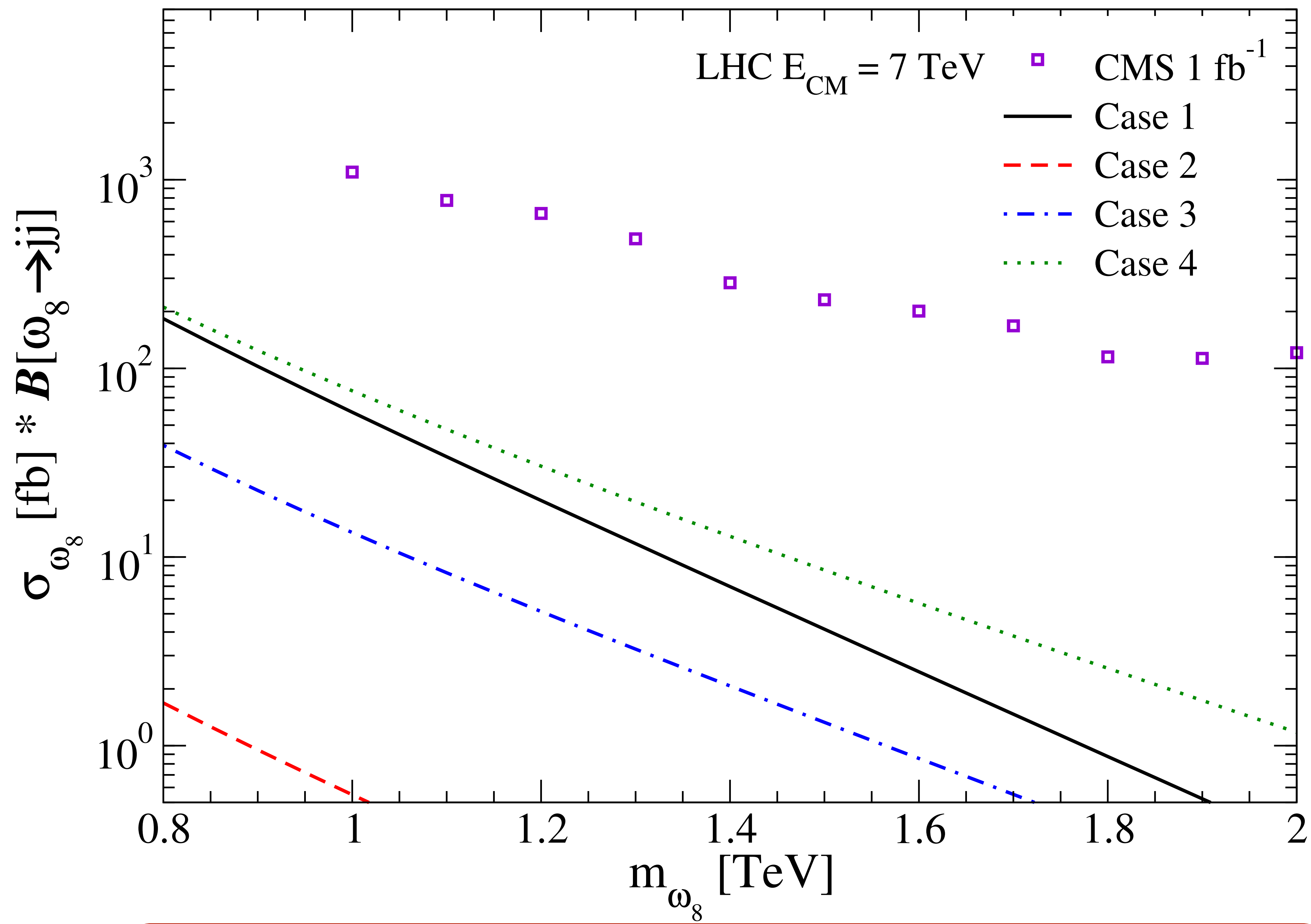


ω_8 is narrow resonance with $\Gamma_{\omega_8} \sim \text{few GeV}$

For case 3, large Δm → $\Gamma_{\omega_8} \sim 20 \text{ GeV}$

Dijet rate times total cross section of ω_8

CMS dijet direct search constraint at 7 TeV 1 fb^-1



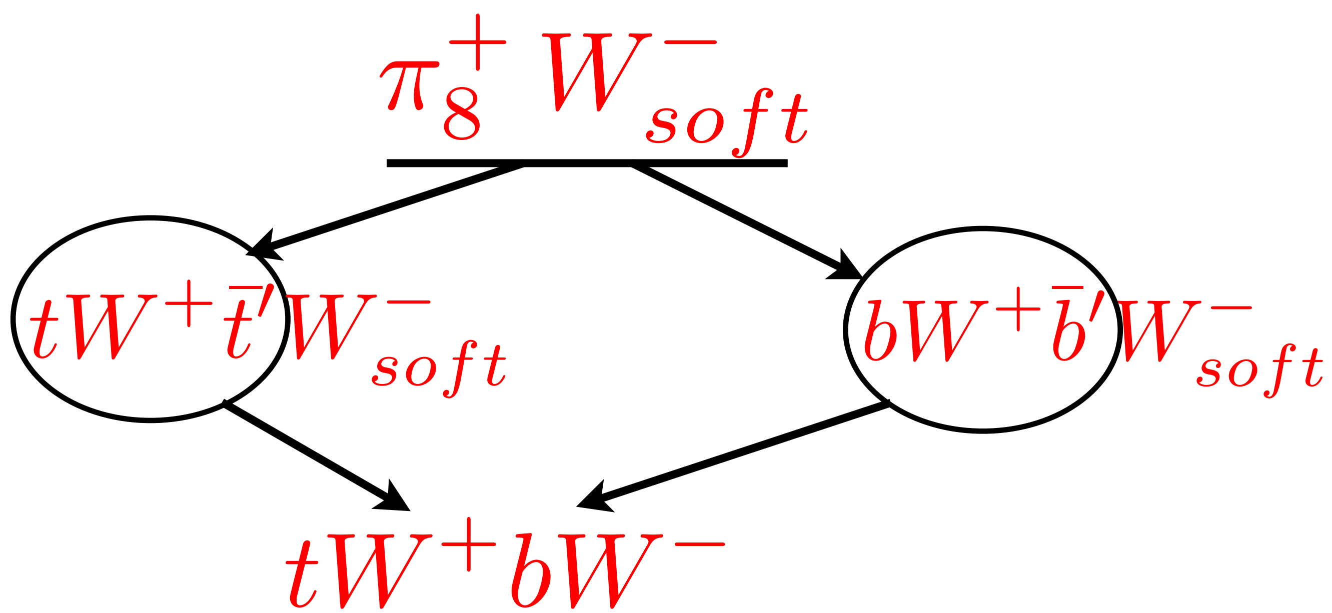
Dijet rate is at most 1/10 of CMS constraint
If $\Delta m < M_W$, could reach the current bound

Discussion

Signal for $q\bar{q} \to \omega_8 \to \pi_8 W_{soft}$

With soft W & Z, final state is complex for free decay

Charged octet pion channel: W_{soft} + 7jets system



If boosted t & W can be used to isolate, W_{soft} can be a tag
Can be included in $t\bar{t}W$ search
If total jet mass resolution is good both colored pion and omega can be discovered

Neutral octet pion channel

$$\pi_8^0\, Z_{soft} \rightarrow \{bW^+\bar{t}', tW^-\bar{b}'\} Z_{soft}$$

Multijets with *t* & *W* substructure, *Z +6/8jets* narrow resonance
Dilepton ID for *Zsoft* reduces branching fraction

For case 4 with small mixing, the signal gives *W g* resonance of ~TeV

$$\pi_8 W \rightarrow \{W^+ g W^-_{soft}, Z g Z_{soft}\}$$

fairly unique. Study is ongoing, tune in for next talk

$\omega_8 \to \pi_8 \gamma$ <1%, but photon detection efficiency high

Conclusions

- 4G quarks with 500-700 GeV mass could result Yukawa-bound mesons.
    - Studies of strong Yukawa suggest heavy mesons of 4g
    - Spectrum is determined by isospin dependent Goldstone potential
- Spectrum very distinct from models like technicolor
- We studied their phenomenology at early run of LHC
    - Production of color-octet isosinglet vector resonance ("*g-prime*")
- Color-octet "*pion*" mostly decay via free quark decay leading to multijet final states or as *Wg* resonance for small mixing
- Their presence give more complex phenomena for 4G search than the no-bound state case